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Watershed Studies
Water Conservation

March 14, 1930

STUDIES OF FACTORS AFFECTING THE YIELD OF WATER FROM WATERSHEDS IN SOUTHERN CALIFORNIA

By

W. C. Lowdermilk, Ph D., Senior Silviculturist
California Forest Experiment Station

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A paper presented before the conference on Research Problems in Consumptive Use of Water and Conservation of Rainfall under the auspices of the Committee on "Contributions to Groundwater Supplies from Rainfall and by Spreading of Streams" of the Irrigation Division of the American Society of Civil Engineers, Los Angeles, March 27-28, 1930.

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RS
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Studies of factors affecting the yield of water from watersheds in southern California

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The object of this paper is to examine the problem surrounding the use of water by the chaparral forests which predominantly cover the water yielding drainages of southern California, and to report briefly the results of certain experimental studies of particular phases of this problem. As will be evident below, the question is not only how much water do chaparral or brush forests use, but how much retention water can be reduced, and how much can be carried over in slope soils from one rainy season to another. The answer to this question will not furnish the sole basis for the management of watersheds for water production; for accelerated erosion among other factors must also be considered. Yet both transpiration and evaporation make up such large portions of precipitation supplies of water as to require careful determination as a basis for measures for maximum yield of beneficial and sustained water supply.

The treatment in this paper is confined to mountain watersheds whose yield of run-off water supplements the overhead rains in valley floors. Approximately 4 square miles of watershed are required to yield sufficient water to irrigate one

square mile of the valley floor in addition to overhead rain. The problem of the contribution of rain on the valley floor to ground water supplies is not considered in this paper.

Accordingly we are here concerned with:

1. Supply, and
2. Disposition of meteoric waters

The following analysis furnishes the basis of treatment of the subject to be followed in this paper. This analysis will also serve to indicate which phases of the problem have thus far been subjected to experimental study, and the relationship of these studies to the problem as a whole.

An analysis of the supply and disposition of meteoric waters

I. Supply of meteoric waters, comprises;

1. Amount and occurrence as,

1. Rain
2. Snow
3. Cloud drip
4. Fog drip
5. Intra solum condensation

2. Effectiveness of supply for ground water replenishment is conditioned by;

1. Distribution
2. Intensities
3. Duration and amount by storms
4. Weather conditions between storms
5. Time of fall in relation to growing season.

Heavy and prolonged storms furnish the principal replenishment to underground supplies under otherwise similar conditions. Thus intra solum condensation, fog drip and cloud drip as well as light rains while playing an important role in supporting the growth of vegetation, are of little or no importance in replenishment of ground water supplies.

II. The disposition of meteoric waters comprises;

1. Retention, (consumptive use) being;
   i. Evaporation,
      (a) From foliage
      (b) From soil surfaces
      (c) From soil mass by vapor movement
   ii. Transpiration,
      (a) From chaparral forests on drained slopes.
      (b) From subirrigated canyon bottom vegetation.
   iii. Water of combination, to form,
      (a) Organic substances
      (b) Hydrates of oxides and silicates in rock weathering processes.
   iv. Abysmal seepage.

2. Run-off, being;

   i. Ground water drainage, (springs).

   ii. Storm flow, combining;
   (a) Shallow seepage or the discharge of wet weather springs.

   (b) Superficial or surficial run-off which represents the unabsorbed portion of rainfall or melting snow. Surficial run-off has been a factor subjected to detailed experimental studies.

3. Deep seepage, or deep penetration which escapes by slow percolation through rock masses without following drainage channels.

I. Supply of meteoric waters

The supply of meteoric waters in southern California is derived chiefly from Pacific Ocean Cyclonic storms invading the land area. It occurs predominantly as rain and snow. The total supply of precipitation has been determined adequately in only a few instances. Very few of our watersheds are equipped with instruments to measure the intensities as well as amounts of rain to a degree satisfactory for calculating the total catch of watersheds. While the measurement of rain presents certain problems in accuracy, the measurement of snow involves the dealing with still larger errors. A first requisite in studies of the disposition of meteoric waters is a measurement of precipitation supplies within a determinable degree of accuracy.

The following criterion of adequacy of rain gages is suggested. Rain gages will be considered sufficient in number and correctly located when the values of catches by isohyetal zones show the same relationship to a frequency distribution as the catches of all individual rain gages employed on the catchment area. (Also see Whitney 1929).

But rain and snow do not comprise the sole source of meteoric waters. We know thus far little about fog drip, cloud drip and intra-solum condensation. Fog drip is common in the fog belt of California and during the rainless season brings to the ground observable quantities of water. The importance of this source is not yet fully known. Cloud drip is common above the cloud line over the state. Cloud drip has been recognized by many students of water supplies, (Schubert 1917, Perez 1925, Brookes 1928.) Descombes (1918, 1922-3) was obliged to consider cloud drip or "occult condensation" in addition to measured precipitation to account for total run-off in watershed studies in the Pyrenees. The comparative studies of Dr. W. P. Hoge of the Mt. Wilson observatory furnish rather startling results, (1919). Gages beneath trees received as much as 265 per cent of the catch in the open. These results can be accepted only as an indication of a phenomenon, which is common in our mountains, and which requires further study. Intra-solum condensation is the direct condensation within the soil of moisture from the air. Lebedeff (1928) has experimentally

determined that such condensation takes place under certain conditions. It is probable, however, that intrasolum condensation plays an insignificant part in the yield of watersheds in streamflow.

Certain important conditions determine the effectiveness of the supply of meteoric waters for yield in irrigation water. Gilman (1930) and Blaney (1929) have called attention to the necessity of recognizing the influence of intensity and distribution of rains on yield and penetration. The total amount of precipitation is no satisfactory measure of the effectiveness of the season's fall. The more important of these conditions are:

1. Distribution
2. Intensities
3. Duration and amount by storms
4. Weather conditions between storms
5. Time of fall in relation to growing season.

Factors which determine the effectiveness of precipitation have not thus far received adequate attention. Such determinations precede in importance the modifying influence of other factors. Methods of experimentation which have recently been employed to measure the effectiveness of precipitation will be considered below under the heading of evaporation and transpiration.

II. Disposition of meteoric waters

The disposition of the aggregate supply of meteoric water is even more complex. Precipitation becomes;

1. Retention (consumptive use)
2. Run-off
3. Deep seepage, or deep penetration

Deep seepage refers to water percolating through rock masses into valley basins without following surface drainage channels. Geological structure of country rock primarily determines the amounts of deep penetration. It is probable, however, that the rapid lowering of water tables in the valley fill basins of southern California has increased the amounts of deep penetration over those of the pre-agricultural period in this region. These amounts of water are indeterminate, but may be small in comparison with the discharges of drainage channels.

Run-off, as has been indicated in the analysis, includes the surface streamflow and subsurface flow in detrital filled drainage channels. This fraction has been divided into,

1. Ground water drainage, and
2. Storm flow

Ground water drainage is the aggregate flow from springs. It lags behind rainfall in a manner characteristic of each watershed. The studies of Shuman (1929) have correctly indicated this. This lag in flow involves temporary underground storage which will interfere with the accuracy in such an equation as;

$$P = R + E$$

where P = precipitation
R = run-off
E = evaporation opportunity, or consumptive use or retention.

When deep seepage is ignored, the more correct expression is:

$$P = R + E \pm St$$

where S_t = temporary underground storage

Storm flow, on the other hand, represents the flow in excess of ground water drainage responsive to storms of rain and snow. Storm flow requires further division into:

a. Shallow seepage, or the discharge of wet weather springs, and

b. Superficial run-off or surficial run-off, which represents the unabsorbed portion of rainfall or melting snow.

Significance of surficial run-off

The fraction of surficial run-off has been the object of a special series of experimental studies. A careful survey of the important stream flow studies from the time of Belgrand (1853) to the present has disclosed remarkable discrepancies in conclusions from observed data. The conclusions of Chittenden (1909), Moore (1910) and Mead (1911) among others which attribute no influence of the mantle of vegetation on streamflow can not be made to jibe with the specific findings of Demontzey (1878), Descombes (1918), Sampson (1918), Duley and Miller (1923) and others. It is plain that the state of our knowledge in this field is not satisfactory. Experimentation is not yet complete until we are in a position to explain the discrepancy in the divergent conclusions just cited.

In attacking this problem the writer early suspected that the use of stream flow in a large drainage channel is unsatisfactory as a measure of a single modifying factor on the run-off ratio from a watershed (1930). Such a stream is a resultant of many modifying factors on the yield of run-off from rain. It seemed justifiable, therefore, to isolate the influence of a mantle of vegetation on the division of precipitation waters at the zone of impact on the land surface into penetration and surficial run-off. It is apparent that this is the point at which vegetation exercises its maximum influence not only on the disposition of waters but on soil erosion.

The general line of attack in the study of the influence of mantles of vegetation on the economy of waters and erosion of soil, therefore, involves the isolation of factors experimentally and to follow these influences progressively into larger and larger units of a watershed to large drainages. At the present time only one phase of the study has been completed. The results of the series of studies on the factors affecting surficial run-off and erosion of soil profiles have been reported elsewhere (1926, 1930) but will be summarized briefly here for the purposes of this paper.

Methods of study of surficial run-off

Serious difficulties encountered by the writer in the measurement of torrential run-off, highly charged with debris, were the occasion for the adoption of the run-off plot for experimental studies.*

The run-off plot comprises an area of 1000 to 1200 square feet or more equipped with inset borders to prevent the incursion of surficial run-off from outside and to prevent the escape of surficial run-off except through the outlet in a baffle trough into a sediment trap thence into an automatic recording measuring device of large tipping buckets. The tipping buckets are calibrated to measure and record 0.1 cubic feet at each tip. Rainfall is likewise measured for intensity and amount and is automatically recorded on the same recording sheet. This equipment makes it possible to correlate the rate of surficial run-off from the plots with both intensities and amount of rain by 5 minute intervals.

The plots are located in undisturbed cover of vegetation and on adjacent surfaces burned clean of vegetation to measure the comparative influence of the mantle of vegetation on the absorption of rain by the soil, and upon erosion.

*Note. The experiments by C. J. Kraebel of the California Forest Experiment Station with installations of the Venturi flume as adapted by Parshall hold great promise for satisfactory measurement of silt and debris laden torrential flows.

Plots are installed inpairs to establish a measure of experimental variation encountered in sampling. As far as can be determined all conditions are selected for uniformity as nearly as possible except that of the condition at the soil surface, which is in this phase of the study the particular factor under comparison.

The results of the run-off plot experimentation have indicated conclusively that a natural mantle of vegetation maintains the soil of a landscape in a condition of greater absorption than the same soil bared of its natural cover of vegetation. This influence is most conspicuous under intensities of rain exceeding the rate of 1.0 inch per hour. This influence on absorption exceeds in an important degree the absorption capacity of the layer of vegetable litter beneath the forest or vegetative mantle. This finding is at distinct variance with the conclusions of Chittenden, Moore, Mead and others.

These experimental plots have during the past three rainy seasons been subjected only to comparatively light rain storms. Rain intensities have scarcely exceeded the rate of 1.0 inch per hour in any instance and then only for short intervals of time. It can only be conjectured what results would follow the high intensities which have been measured in storms in southern California.

The study was pursued further to discover how this influence is exercised. Accordingly an experiment was set up at Berkeley in 1927 to study the role of forest litter apart from its vegetation. The details of this experiment are reported by the writer elsewhere, (1930). In short, 8 tanks were installed, each to provide for a projectional area of 10 square feet, a soil profile of 2.5 feet and a slope of soil surface of 30 per centum, as well as for the application of artificial rain. The equipment provided for collecting surficial run-off, for leading it through a sediment trap, and thence into a collector tank graduated for reading volume direct. Seepage after passing through the soil profile was conducted directly into seepage collector tanks likewise fitted with graduated gages for measurement.

Three typical forest soils were sampled in shallow layers of 1 to 4 inches deep and returned to the tanks in natural order, and to their field volume as nearly as possible. The macro-structure within the soil, due to the burrowing of insects, rodents and to decaying roots was of necessity destroyed and could not be duplicated in the tanks. It was, however, the purpose to produce as nearly as possible uniform media of percolation for the tanks containing each soil series. This experiment was designed specifically to isolate the influence of forest litter on penetration and erosion, and would consequently require such treatment rather than the use of natural undisturbed profiles.

Forest litter belonging to each soil sample was replaced. After a period of weather settling during the rainy season of 1927-28, the litter on the odd numbered tanks was burned off clean. The experiment was ready for the comparison of surficial run-off and erosion from bare and litter covered soil surfaces.

Besides natural rain, artificial rain to a total depth of 198 inches was applied in 6 series of 10 runs each, over a period of 6 months. The application of artificial rain varied from 1/2 to 8 hours by series of 10 uniform runs. Intensities varied between 0.5 to 2.0 inches per hour.

Table 1a.

Summary of artificial rain and comparative surficial run-off
by
Series° and Tanks

Aiken Soil Series loam - Tanks I and II

Tank I soil surface burned bare; Tank II soil surface covered with natural forest litter

Tanks		:By Series of 10 runs each - Depths in inches: A°°	B	C	D	E	F	G
(Duration of each run			1 hr.	2 hrs.	4 hrs.	8 hrs.	1/2 hr.	1½ hr.
I	Rain	5.68	12.05	16.05	39.87	52.01	6.56	14.28
	Run-off	.17	1.73	4.41	13.13	18.95	2.02	3.40
II	Rain	5.68	14.69	19.18	45.48	67.07	7.13	18.14
	Run-off	0.07	0.48	0.59	1.80	3.09	0.07	0.49

Comparison of surficial run-off in percentages of rain by tanks.

I (Litter burned)	3.0	14.3	27.4	32.9	36.2	30.8	23.8
II (Litter intact)	1.2	3.2	3.0	3.9	4.6	0.9	2.7

° Note. Each series comprised 10 runs of uniform duration 1 or 2 days apart.

°° Note. Natural rain totaled from March 8 through April and May.

Table 1b.

Summary of artificial rain and comparative surficial run-off by series and tanks.

(Holland)-Stanislaus Soil Series (fine sandy loam), - Tanks III and IV.

Tank III soil surface burned clean; Tank IV soil surface covered with natural forest litter.

Tanks		By series of 10 runs each - Depths in inches: A*	B	C	D	E	F	G
(Duration of each run			1 hr.	2 hrs.	4 hrs.	8 hrs.	1/2 hr.	1½ hr.)
III	Rain	5.66	15.27	21.13	44.03	75.24	8.19	20.77
	Run-off	0.11	9.12	6.05	12.38	17.75	3.37	4.05
IV	Rain	5.68	15.95	22.59	46.24	80.00	8.36	22.47
	Run-off	0.08	3.61	2.70	6.15	8.53	1.34	0.94
	Comparison of surficial run-off in percentages of rainfall.							
III	(Litter burned)	1.9	59.7	38.0	28.1	23.5	41.1	19.6
IV	(Litter unburned)	1.4	22.6	11.9	13.3	10.6	16.0	4.1

*Note. Natural rain totaled from March 8 through April and May.

Table 1c.

Summary of artificial rain and comparative surficial run-off by series and tanks.

(Altamont) Soil Series: Berkeley Hills. Tanks V and VI.
(Clay loam)
Tank V soil surface burned clean: Tank VI soil surface covered with natural forest litter.

Tanks		:By series of 10 runs each - Depths in inches: A°	B	C	D	E	F	G
(Duration of each run			1 hr.	2 hrs.	4 hrs.	8 hrs.	1/2 hr.	1½ hr.
V	Rain	5.68	17.23	23.01	45.61	83.91	8.12	23.49
	Run-off	0.95	7.17	14.44	19.33	47.70	2.25	14.44
VI	Rain	5.68	17.92	23.44	44.84	88.89	8.43	24.96
	Run-off	0.06	0.31	0.88	2.38	3.12	0.09	0.63
	Comparison of surficial run-off from tanks in percentages of rainfall.							
V	(Litter burned)	16.7	41.6	62.7	42.4	56.8	27.7	61.5
VI	(Litter intact)	1.0	1.7	3.7	5.3	3.5	1.0	2.5

°Note. Natural rain totaled from March 8 through April and May.

Table 1d.

Summary of artificial rain and comparative surficial runoff by series and tanks.

(Altamont) Soil Series: Berkeley Hills. Tanks VII and VIII in duplicate. (Clay loam.)

Tank VII, soil surface burned clean: Tank VIII soil surface covered with natural forest litter

Tanks		:By series of 10 runs each - Depths in inches: A*	B	C	D	E	F	G
(Duration of each run			1 hr.	2 hrs.	4 hrs.	8 hrs.	1/2 hr.	1½ hr.)
VII	Rain	5.68	17.62	22.46	42.77	88.68	8.25	24.55
	Run-off	1.12	7.67	14.80	17.42	46.17	2.62	14.90
VIII	Rain	5.68	12.82	14.52	36.68	82.70	7.83	22.93
	Run-off	0.15	0.53	1.07	1.91	3.64	0.11	0.69
	Comparison of surficial run-off in percentages of rainfall.							
VII	(Litter burned)	19.7	43.5	65.8	40.7	52.0	31.7	60.7
VIII	(Litter intact)	2.6	4.1	7.3	5.2	4.4	1.4	3.0

*Note. Natural rain totaled from March 8 through April and May.

Table 2.

Erosion from tank surfaces by series of applications of artificial rain and weight ratio of silt to run-off water.
-Arranged according to chronological order of runs-

Item	TANKS I	II	III	IV	V	VI	VII	VIII
	Series B. 10 runs of 1 hour each							
Weight, grams	40.60	0.40	656.75	1.70	516.80	0.300	670.65	0.90
Ratio, %	0.10	0.035	0.30	0.02	0.31	0.041	0.37	0.07
	Series C. 10 runs of 2 hours each							
Weight, grams	89.65	0.35	235.60	0.59	1003.50	0.43	1472.93	3.61
Ratio, %	0.86	0.025	0.12	0.009	0.260	0.002	0.42	0.014
	Series D. 10 runs of 4 hours each							
Weight, grams	35.40	0.45	19.02	2.48	437.35	0.500	370.81	1.0
Ratio, %	0.001	0.0001	0.006	0.001	0.1	0.001	0.09	0.002
	Series E. 10 runs of 8 hours each							
Weight, grams	48.65	0.50	235.60	1.07	2253.7	0.30	1910.6	0.95
Ratio, %	0.01	0.0007	0.05	0.0005	0.200	0.0004	0.18	0.001
	Series F. 10 runs of one-half hour each							
Weight, grams	18.60	0.05	234.02	2.00	275.80	0.60	295.10	0.42
Ratio, %	0.040	0.003	0.30	0.086	0.520	0.030	0.46	0.016
	Series G. 10 runs of 1-1/2 hours each							
Weight, grams	38.15	2.00	28.10	0.950	1317.70	0.400	1241.20	0.47
Ratio, %	0.047	0.017	0.030	0.004	0.383	0.0027	0.353	0.0028
	Aiken Soil Series-a loam		Holland Sierra Series-a fine sandy loam		Altamont Series-a clay loam		Altamont series in duplicate	

Figure 1.

Studies of factors affecting the yield of water from watersheds in southern California.

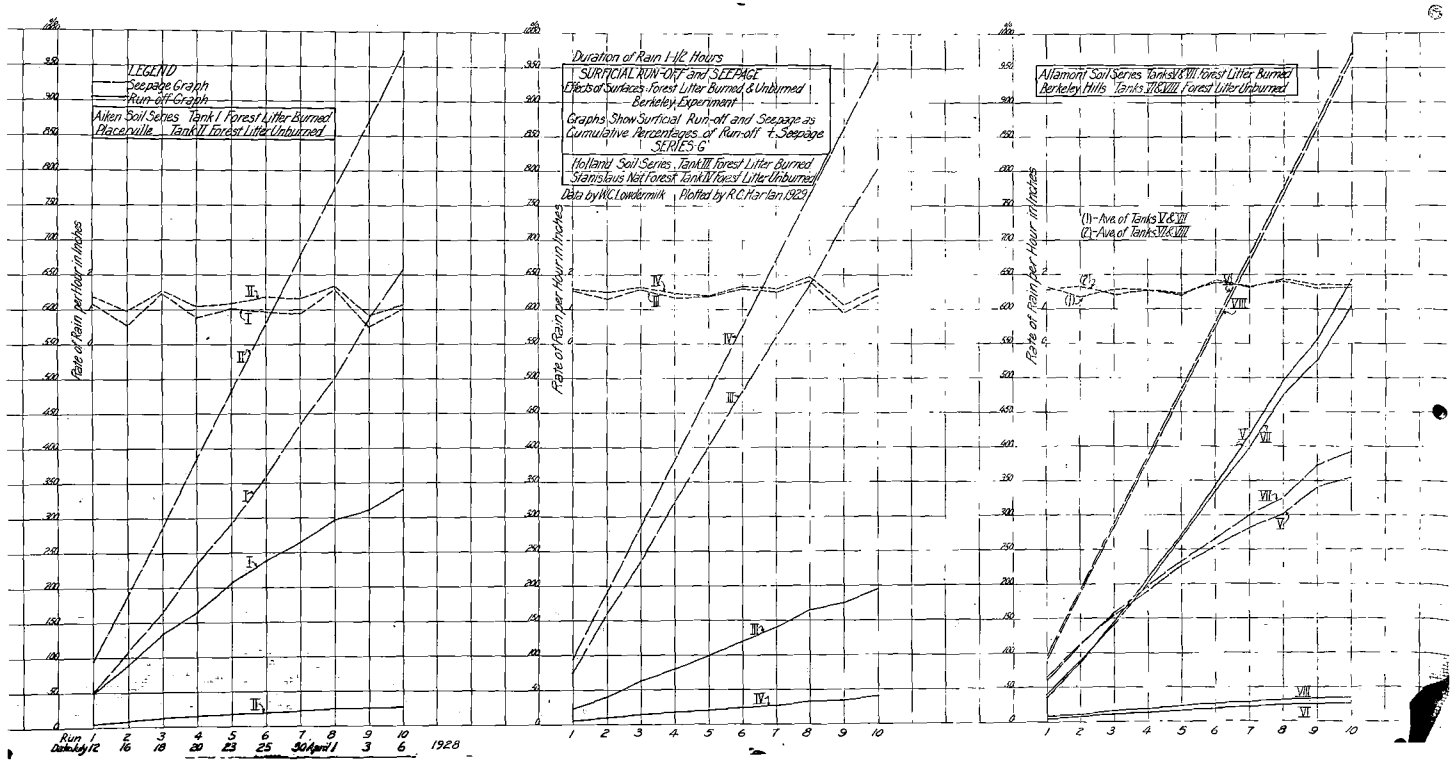

LEGEND
Seepage Graph
Run-off Graph
Aiken Soil Series Tank I Forest Litter Burned
Placerville Tank II Forest Litter Unburned
Rate of Rain per Hour in Inches
Run 1 2 3 4 5 6 7 8 9 10
Dec. July 12 16 18 20 23 25 30 April 1 3 6 1928
Duration of Rain 1-1/2 Hours
SURFICIAL RUN-OFF and SEEPAGE
Effects of Surfaces, Forest Litter Burned & Unburned
Berkeley Experiment
Graphs Show Surficial Run-off and Seepage as
Cumulative Percentages of Run-off + Seepage
SERIES G
Holland Soil Series Tank III Forest Litter Burned
Stanislaus Nat. Forest Tank IV Forest Litter Unburned
Data by W.C. Lowdermilk Plotted by R.C. Harlan 1929
Rate of Rain per Hour in Inches
Allamont Soil Series Tanks V & VII Forest Litter Burned
Berkeley Hills Tanks VI & VIII Forest Litter Unburned
(1) - Ave. of Tanks V & VII
(2) - Ave. of Tanks VI & VIII
Rate of Rain per Hour in Inches

Plate I.

Surficial run-off and erosion studies
Devil Canyon Installation

A view of the collecting and automatic measuring and recording devices installed on run-off plots. From a baffle trough at the bottom of a plot the run-off is lead through a sediment trap constantly filled of water into the automatic run-off tipping bucket and recording mechanism.

---W. C. Lowdermilk,
California Forest Experiment Station.

Plate II.

Surficial run-off and erosion studies
The role of forest litter.

A view of the tank installation at Berkeley, California where artificial rain to a depth of approximately 198 inches in six months was applied in 70 runs varying in duration by series of 10 runs each.

----W. C. Lowdermilk,
California Forest Experiment Station.

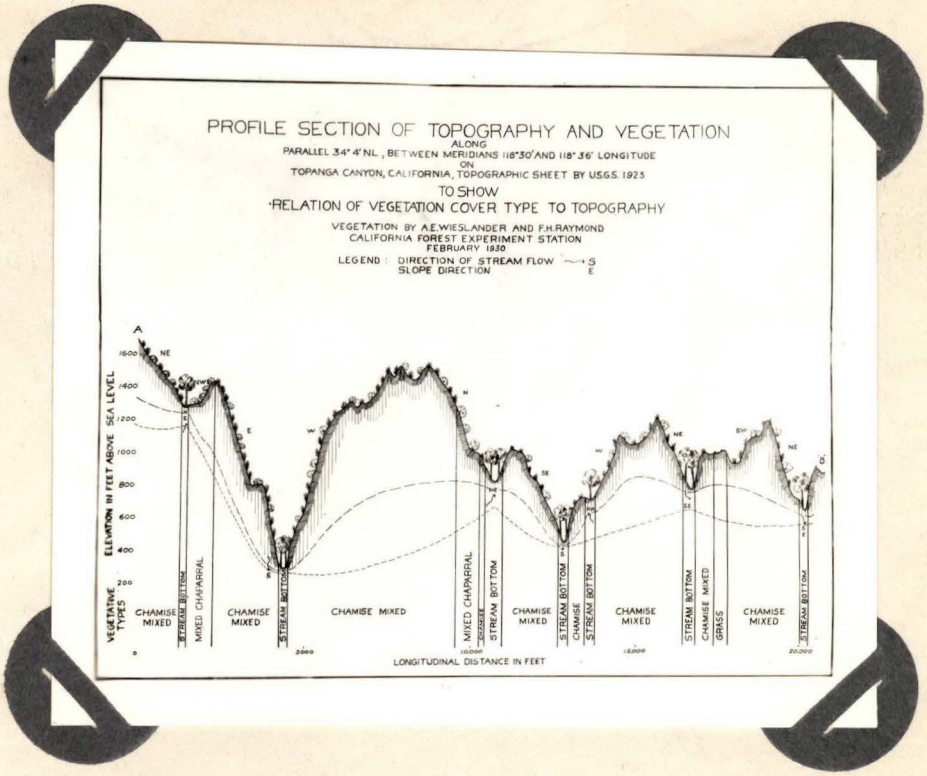
Plate III.

Transpiration from mountain vegetation.

A map of vegetative types to be found on a typical area of chaparral forests in southern California. The division into stream bottom and drained slope vegetation is shown by hachures.

---W. C. Lowdermilk,
California Forest Experiment Station.

Plate IV.



Transpiration from mountain vegetation.

A profile section along A.B. of Plate III where the vertical scale is 5 times the horizontal scale to show the relation of vegetative types to topography.

--W. C. Lowdermilk,
California Forest Experiment Station.

Plate V.

Transpiration from mountain vegetation.

A view of a portion of the San Gabriel watershed showing the distinct nature of stream bottom vegetation in contrast to slope vegetation which is made apparent by a forest fire.

Plate VI.

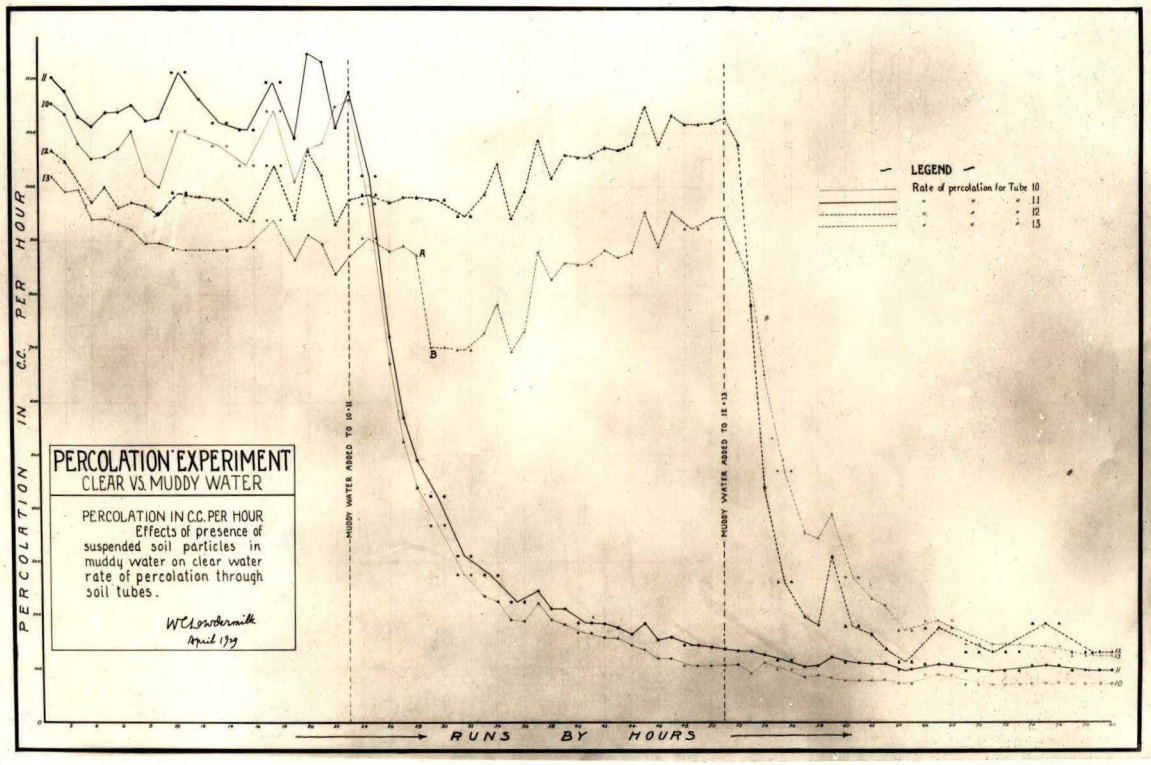
Water Relationships,
Devil Canyon Installation.

A view of rain retention pans designed to measure the effectiveness of rain penetration through 4, 8, and 12 inch layers of soil. Instruments designed to measure interception, retention and evaporation and transpiration from soils are located in the chaparral cover on the opposite slope.

---W. C. Lowdermilk,
California Forest Experiment Station.

Figure 2.

Studies of factors affecting the yield of water from watersheds in southern California.


PERCOLATION IN C.C. PER HOUR
RUNS BY HOURS
MUDDY WATER ADDED TO 10-11
MUDDY WATER ADDED TO 12-13
A
B
LEGEND
Rate of percolation for Tube 10
" " " 11
" " " 12
" " " 13
PERCOLATION EXPERIMENT
CLEAR VS. MUDDY WATER
PERCOLATION IN C.C. PER HOUR
Effects of presence of suspended soil particles in muddy water on clear water rate of percolation through soil tubes.
W.C. Lowdermilk
April 1934

resulting from pH reactions, a concluding experiment was designed to discover the comparative rates of percolation of clear and muddy water. The installation consisted of 4 soil tubes 8 inches in diameter and numbered 10, 11, 12 and 13. They were filled with a uniform fine sandy loam. It was equipped to maintain an inch head of water over the soil in each tube, and for the inclusion of a fine screen to prevent the development of currents of water above the soil surface.

Clear water was percolated through all four tubes for a week to discover the percolation characteristics of each tube. Thereupon muddy water containing 1.8 ± 0.1 per cent of sediment by weight was applied to Tubes 10 and 11 for a week. The rate of percolation rapidly dropped off to less than 1/10 of the clear water rate. See Fig. 3. Clear water was run through the Tubes 12 and 13 simultaneously. At the end of the second week muddy water was applied to Tubes 12 and 13 and clear water again to Tubes 10 and 11. The rate of percolation dropped off in Tubes 12 and 13 in a similar manner, but the rate did not change in Tubes 10 and 11. The percolate in every instance was clear, showing that the suspended soil particles were filtered out at the surface.

These decisive results are concluded to indicate that the filtering of a muddy suspension at the surface of a soil establishes a thin layer of fine textured material which reduces the rate of percolation through the entire column or profile of soil. The action of a muddy suspension induced

by surficial run-off on a bare soil surface in reducing the rate of percolation at the surface is presumed to account chiefly for the major differences in surficial run-off in the Berkeley run-off and erosion experiment.

Likewise it is possible to understand more specifically than hitherto how a mantle of vegetation functions in maintaining the percolating capacity of a soil profile under natural conditions. Forest litter is concluded to be the most important part of the forest in its influence upon penetration of rain into soils. And its capacity to absorb moisture to as much as 5 times its weight is insignificant in comparison with its function to protect the natural macro-structure of a soil and to maintain the soil's capacity for percolation of rain water.

These studies emphasize the importance of certain principles in the conservation of rain and control of water and erosion. The soil sheath of a landscape is the primary agent of absorption and temporary storage of supplies of precipitation water. The processes of soil development, responsive to parent material, climate, vegetation and time, have produced soil profiles which are adapted to the absorption of the prevailing quantities of precipitation, and therefore represent the maximum capacity for absorption of rain waters under the given conditions. The interaction of rock weathering and vegetation has within recent geologic time produced a soil mantle subject to a geologic norm of erosion.

The mantle of vegetation is of first importance in maintaining the norm of erosion under given conditions. The destruction of the protective mantle of vegetation, therefore exposes the accumulated soil layer to erosion processes of an accelerated order. Attendant on the baring of the soil sheath is not only the loss in depth of the porous soil layer, but the sealing of the surface of the soil profile. These results are demonstrable at the inception of processes of surficial run-off and erosion. Other modifying factors begin to operate on run-off discharge as it accumulates from larger and larger areas until it becomes difficult to relate the resultant characteristics of streamflow to a single modifying character within a watershed. The sediment or silt, however, remains the most sensitive index of changes in the normal run-off conditions of watersheds.

These studies contribute only indirectly to the problem of the transpiration factor in the disposition of meteoric waters. Of particular importance is the role of temporary storage in the soil mantle which the mantle of vegetation maintains to its possible maximum. This is produced by the macro-structure of the soil, which is brought about by insects, worm and burrowing animal life which directly or indirectly finds its food supply in the vegetation. Likewise the channels formed by decayed roots further contribute to a structure which is entirely independent of the textural characteristics of a soil. In this respect

the capacities for temporary storage of natural forest soils is an entirely different quantity from that of cultivated soils.

The value of this temporary storage is not called into play except in the more prolonged rains or in wet years, when it may reach high values, in water and erosion control.

Retention or consumptive use

The third factor in the disposition of meteoric waters is retention of water by the catchment area. It is also designated "consumptive use". Retention or consumptive use may be further divided into:

i. Evaporation,
ii. Transpiration
iii. Water of combination
iv. Abysmal seepage

Abysmal seepage, being that which penetrates to great depths in consolidated rock, may be assumed to have saturated the rock in past geologic time. It could be increased by uplift of the land surface. Geologically rapid rates of uplift are assumed to render such amounts of water of little significance in water conservation schemes in southern California.

Water of combination is withdrawn in the formation of organic and inorganic compounds. Water combined in

organic substances is returned to the atmosphere as vapor as they decompose. This quantity is small and represents approximately 0.1 per cent of transpiration of plants, (Livingston & Shreve 1921). Inorganic compounds include hydrated oxides and silicates, resulting from the weathering of rock. This withdrawal is relatively permanent, but is of small moment in water supplies.

Transpiration

Transpiration includes water taken up by roots and given off from the aerial parts of plants. The principal portion of transpiration is given off through leaves. The stems as well as dead plants give off small quantities of moisture to the atmosphere.

As far as is known no studies of transpiration have been made which serve to indicate the transpiration losses from chaparral forests by area in southern California. Data including the combined amount of transpiration and evaporation, do not permit the segregation into component values without experimental study.

The following general features of the problem have received consideration in the present undertaking by the California Forest Experiment Station to study transpiration losses experimentally. This analysis is presented for discussion by this group. It is essential that all phases of the problem be considered in conducting experimental determinations.

The first feature to be considered is the relation of the rainy to the growing season. Winter rains and dry summers simplify this problem in one particular. The degree of arrested growth in winter varies with altitude and latitude. In the valleys of southern California the growth of evergreen plants is much retarded, or completely stopped. The transpiration losses during winter are much less than during the favorable growing temperatures of summer. At increasing altitudes up canyons and mountain slopes transpiration decreases to a minimum at snow line. Likewise the length of the growing season varies in length with altitude, being longest, of course, at valley elevations.

Growing and rainy seasons are coincident to a varying extent. Overlaps of favorable growing temperatures above a diurnal average of 40° F. (Livingston and Shreve 1921), and rainy seasons vary also with altitude. It is necessary to determine the importance of transpiration during the overlap periods for the entire range in altitude.

The second important feature of the problem in southern California is the recognition of two major types of vegetation included within the watersheds of the region. They are, (1) the vegetation confined to drained slopes, and (2) the canyon bottom or stream side vegetation which enjoys sub-irrigation throughout most or the entire period of favorable growing temperatures. The sharp division between these two types is discernable from vantage points on ridges. Type

maps now being made under the supervision of A. E. Wieslander of the California Forest Experiment Station clearly show the type boundaries and the comparative area covered by each type. These distinctions become less conspicuous with increase in altitude above the cloud line.

These two types of vegetation are believed to have widely different quantities of water at their disposal. On the drained slopes the water holding capacity or field capacity of the soil less the moisture at the wilting point represents all the moisture available to vegetation after the last rain in spring. After the chaparral forest has extracted the easily available moisture it must survive on very small amounts of moisture throughout the remainder of long seasons favorable to growth. Pearson (1926) found that pine (Pinus ponderosa) and Rocky Mountain Douglas fir (Pseudotsuga taxifolia) rapidly consume available water, but are capable of surviving for long periods of time on very small quantities of moisture. It seems probable that chaparral vegetation is required to do this. Its dwarfed form is doubtless a response to the limiting factor of moisture.

On the contrary, the vegetation in canyon bottoms has all the water it can use at its disposal throughout the summer. The species of the vegetation are unmistakable indicators of this condition. They are willows, alders, sycamores, grapevines, all of which transpire great quantities of water which Rowe (1924) found at the mouth of White Water

River to approximate the evaporation from a free water surface, a total of about 8 acre feet per year.

These considerations have an important bearing on explanations of observed increased flow in streams and the opening of small springs at the lower ends of willow flats following forest fires. It is, for this reason, probable that such increases in flow come from a reduction in transpiration losses from the subirrigated canyon bottom vegetation rather than from the chaparral vegetation on drained slopes. In fact, it is impossible to see how a fire would cause the slope soils to give up any of their capillary water to underground flow. On the contrary forest fires can be expected to increase evaporation from the soil. Conspicuous soil slides following fires are indicative of a powder dry condition of soil which fire has produced.

More significant still is a consideration of the possibility of carrying field capacity water in drained soil from one rainy season to another. To increase the yield of water from drained slopes it is necessary to hold over such increases in the soil to the succeeding rainy season, where it is effective in increasing the gravity flow. Summer fires are followed by the rainy season. Under light intensities of rain erosion may not be conspicuous, but under heavy intensities accelerated erosion is a common associated phenomena with burned watersheds. During the following spring burns are reclothed with vegetation in varying degrees. We need

to know more accurately the density and kind of regrowth. Some types of growth such as the chamise (Adenostoma fasciculatum) and oak (Quercus dumosa) sprout vigorously following fires. It is common for a luxuriant growth of herbaceous vegetation to follow fires to be gradually succeeded within about 5 years with the woody chaparral species which formed the original cover. The succession of seeded vegetation is slower on large burns, due in all probability to lack of disseminated plant seed.

The regrowth on burns in the first season, as well as in succeeding years, has before it a long season with temperatures favorable for growth. Temperature is not a limiting factor. The regrowth can be expected, therefore, to grow as long as it has moisture available in the soil. In the case of sprouting vegetation the reach of the roots doubtless is identical with that of the plants before a forest fire. In the case of herbaceous vegetation and new woody plants from seed the roots may or may not reach the depths of the former cover. Yet it seems probable that growth would continue until all available moisture within the root zone was consumed. Thus the height of vegetation is not concluded to be an index of the amount of transpiration on the drained slopes. In fact it appears probable that the sprouting plants transpire more energetically and more water than the mature plants. Experimental determinations are needed to check this hypothesis, which is formulated on an analysis of the factors involved in the problem.

In order, therefore, to increase the yield of water from the drained slopes, it would seem to be necessary to kill the vegetation permanently. Instances exist in California where this has been done by smelter fumes. The Kennett area north of Redding is a good example. It is more than probable that the yield in run-off has been increased in this area over the pre-smelter days. This interesting area, incidentally, offers an unparalleled opportunity to test experimentally the effect of the total destruction of the mantle of vegetation on the yield of water from watersheds. Certainly the evidence is not sufficient to advocate the employment of smelter fumes to increase water supply with the attendant acceleration of erosion, increased turbulency of stream discharge and fatal consequences to agriculture.

It follows that a very fruitful source for increased yield of water is the reduction of transpiration from summer growing canyon bottom vegetation. To cut it or kill it by fire would be both unsatisfactory and would at best net only temporary increases. The method which has been employed in a number of instances, of robbing this vegetation of the drainage flow by collecting and piping it out of the canyon offers the greatest promise. This method is suggested as a certain means of increasing the yield of water from mountain watersheds.

Evaporation

Evaporation may be the most important factor in retention or consumptive use in southern California. When considered as direct losses from wetted surfaces it comprises;

1. Interception by vegetation and its litter
2. Interception by soils

The ratio of evaporation to transpiration will depend on the characteristics of precipitation. If all rain in southern California should occur as 0.5 inch storms one week apart evaporation would account for practically the total supply of meteoric waters. The manner of occurrence of precipitation is doubtless of more importance in determining the supply of underground water than the presence or absence of vegetation on a watershed. Any determinations of the yield of streamflow from rainfall, which does not take into account this feature of the problem not only is incomplete but may actually mislead.

Accordingly determinations of the factors controlling the effectiveness of rainfall are of more importance than those of total amount. The studies of the interception of vegetation by Engler (1919), Munns (1921), Bates and Henry (1928), and Hirata (1929) all indicate that light rains scarcely reach the ground. Only the heavier falls replenish soil moisture.

Exposed bare soils function in a way similar to that of vegetation. The soil layer of the most active capillary movement including a depth to approximately 8 inches

acts in a way analogous to the interception of vegetation. Rains which do not wet below this depth may be lost by evaporation if a few days of clear weather follow storms.

Thus a comparison of the evaporation losses by a mantle of vegetation and by bare soil involves a weighing of relative values. Engler (1919) found as had Ebermayer (1876) and Henri (1908) that whereas the mantle of vegetation reduces the contribution of water to the soil, yet it reduced the evaporation of such supplies that were absorbed by the soil in comparison with the evaporation losses from bare soils.

This phase of the problem required careful experimentation. Experimental studies were undertaken by the California Forest Experiment Station in 1929 to answer some of the questions which have been raised here. The principal objective is to discover the portion of a season's precipitation by amounts and intensities of storms, which passes through vegetation, litter layers, and layers of soil of different depths up to 3 feet. Instruments are designed to measure the following factors:

1. Interception of rain by vegetation
2. Amounts of rain which pass through -
   (a) Litter layers
   (b) Litter and soils of different depths
   (c) Bare soil of different depths
3. Water losses from soil columns 3 feet deep by evaporation, and by transpiration.

A serious experimental difficulty is encountered in these installations. It is the impounding of water by film forces at the interface between water and air of a broken column of soil. Experimental manipulation is being tried to bridge this interface by a system of wicks which connect the soil with a water trap. The success of the device is yet uncertain.

In conjunction with this instrumentation soil moisture sampling is being conducted in a preliminary way at 3 sampling areas. A general systematic attack on the sampling of soil within and without vegetation throughout the year is planned for this and the following year.

Summary

The supply and disposition of meteoric waters have been analyzed into their several factors. Studies of specific factors have been described and their relation and significance to the problem as a whole have been indicated. Points where additional experimental information is needed are set forth. A series of coordinated studies are still necessary to answer adequately what role the chaparral forests play in water economy and conservation in southern California. These as well as other considerations are fundamental in selecting measures for managing mountain areas for the yield of the maximum sustained beneficial water with the minimum of damages from erosion, and other consequences.

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WATER FROM WATERSHEDS IN SOUTHERN CALIFORNIA

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